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MONITORING APPROACHES FOR UTILITY SOLAR WATER HEATING PROJECTS

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ABSTRACT

There have been many solar domestic hot water (SDHW) field monitoring projects, using a wide variety of approaches. The purpose of this paper is to provide a general framework for design of SDHW monitoring projects, with focus on utility objectives. The design of field monitoring projects depends on defining clear objectives, choice of monitoring level, establishment of savings reference, and extrapolation to the population strata of interest. Five objectives are presented and specific project designs are recommended.

1. INTRODUCTION

This paper is intended for those interested in utility field monitoring of solar domestic hot water systems in the context of a DSM program evaluation project. It is focused only on the thermal performance objectives in such a design. Other issues, such as consumer acceptance, aesthetics, reliability, liability and financing, local industry capability, etc. are not treated. Also, the focus is on general experimental design and analysis issues, not on the specifics of instrumentation or measurement problems.

The discussion generally follows ASHRAE guidelines for building energy monitoring (1). The design begins with a definition of objectives of the project: just what do we want to know, and how accurately do we need to know it? The specific problems in attaining the objectives are addressed, along with experimental designs that overcome the anticipated problems. If there is not available an approach consistent with the project budget to achieve the desired objective within the specified accuracy, then the objectives must be modified.

This work was performed to provide technical support for utilities in general and design of monitoring projects for the SMUD SDHW program (2). This paper summarizes the final report (3) which includes bibliographies based on literature searches on: 1) monitoring of SDHW systems and 2) monitoring of utility SDHW projects. The results indicate that many different approaches for monitoring projects have been used, with no overall context for choice of approach. The purpose of this paper is to provide a general framework for monitoring project design.

2. MONITORING OBJECTIVES

Careful definition of objectives is essential, and dictates the optimal experimental design. The objectives in SDHW monitoring will vary, but can be grouped into two general areas: impact assessment (energy impacts and demand impacts) and measured-versus-predicted performance (as-built performance, persistence of savings, and model validation).

Energy Impacts (kWh). The objective is to estimate within a specified accuracy and confidence level (e.g., 10% uncertainty at 90% confidence level) the expected long-term savings in annual household consumed energy for DHW due to installation of SDHW systems, averaged over the target population.

Demand Impacts (kW). The objective is to estimate within a specified accuracy and confidence level the reduction in household and diversified electrical demand due to the installation of SDHW systems as a function of time of day, day of week, and time of year, averaged over the target population. A particular objective may be to estimate the reduction in electrical demand due to the SDHW system for specific utility peak days.

As-Built Performance. The objective is to estimate, for recently installed SDHW systems, how many are performing at 100 percent of predicted performance, how many are performing at a reduced level, and how many are not performing at all. Performance may be assessed in terms of monitored energy savings with the implication that demand reduction can be inferred based on the monitoring energy savings performance levels.

Persistence of Savings. The objective is to estimate the long-term performance of SDHW systems. This is an extension of as-built performance monitoring with the objective to estimate, as a function of time, how many systems are performing at 100 percent of predicted performance, how many are performing at a reduced level, and how many are not performing at all.

Model Validation. The objective is to validate computer simulation models for predicting energy savings and demand reduction. The objective is validation of the model structure and inputs for specific SDHW systems e.g., SRCC OG300 (4) certified systems, not validation of component models in existing computer simulation programs, e.g., TRNSYS (5), which have already been validated. Predictive models are currently used to establish utility DSM subsidy levels and may also be used to extrapolate from a monitored sample to predictions for a more general population.

3. MONITORING LEVELS

Various levels of monitoring are possible depending on how many variables are measured and how often. Demand impact monitoring requires frequent (quasi-continuous) measurements and data logging. Monitoring for energy impacts (or as-built performance or persistence of savings), in principle, requires only measurement of Btu's delivered from the SDHW system totalized monthly or annually. However, to extrapolate from monitoring results to long-term performance for the general population, driving forces (insolation, temperature differences, etc.) need to be known for the monitoring period. In some cases, assumptions or one-time measurements may replace continuous monitoring of some variables in order to reduce monitoring costs to facilitate larger sample sizes. Or, for model validation, additional measurements may be useful for redundant determination of key energy flows and for verifying subsystem or component performance.

There is generally a tradeoff between the level of detail in a monitoring approach, the duration of test, standard deviation of results, and the required/affordable sample size. Low level monitoring typically requires long time duration, has high standard deviation, and thus requires large sample size. Detailed monitoring allows short test duration, has relatively smaller standard deviation in results, and thus allows smaller sample size. Per site costs are significantly higher for detailed monitoring. However, overall cost of a monitoring project is a complex function of method chosen, sample size, and test duration. Within each of the following categories, sublevels exist depending on the specific variables measured.

Billing Analysis. This approach involves analysis of the computerized monthly billing data that utilities have available for all customers at essentially no cost. For each household, a regression analysis will be performed on data from a period before the installation of the SDHW system to develop simple predictive models for space heating and cooling. Using these models with weather data for a period after the SDHW system installation, differences in the heating and cooling loads can be estimated. Savings due to the SDHW system are estimated based on before/after differences in the utility bills, accounting for heating and cooling effects, and assuming that all else remains unchanged (which may not be the case, see Section 4).

End-Use Metering. This approach involves metering of the water heating auxiliary energy use (the back-up heating energy used when the SHDW system does not fully meet the load). The volume of hot water use is also metered and used with estimated/measured inlet and outlet water temperatures to calculate the water heating load (which also includes calculated tank heat losses). The savings due to the SDHW system are estimated based on the difference between the water heating load and the auxiliary energy use. Any parasitic power used by the SDHW system pump(s) is subtracted from the solar savings.

Btu Metering. This approach is similar to the end-use metering approach, but a Btu meter is used to measure the water heating load by continuously multiplying the flow rate by the temperature difference across the water heater. This version of Btu metering applies to either single or two-tank systems and can be performed with a cold water flow meter. Other versions of Btu metering are possible: 1) measurement of the energy transfer from the solar storage to the water heater for two-tank systems, or 2) measurement of the energy transfer from the collector loop to the solar storage for either single or two-tank systems.

Detailed Monitoring. This approach involves measurement and continuous data logging of a large number of variables including each of the major energy flows and the driving forces. This data can be used as in end-use metering as discussed above. Alternatively, the data can be used to validate a model, and impacts calculated indirectly using the model.

4. REFERENCE PERFORMANCE

The objective of monitoring is to establish SDHW system performance relative to the conventional system. Therefore, the performance of the conventional water heating system must be determined to serve as a reference to which the water heating performance with the solar system can be compared. Because water heating energy use depends on a number of factors that vary over time and from household to household, it is important to carefully determine the reference system performance so that a meaningful comparison can be made. The discussion of extrapolation and required sample sizes also applies (in terms of system-days of monitored performance) to establishing equivalency of operating conditions for the reference case and the solar case.

The experimental designs below use different approaches to determine the reference system performance. The first three approaches are statistical in basis and are generally simplest in analysis; they are correspondingly more costly in terms of sample size and data duration.
The various approaches can be combined to produce a more optimal design, such as combining the control group approach with before-after monitoring.

Control Group. The electric usage of a group of households without SDHW systems is compared to a group of households with SDHW systems. The control group needs to be as "equivalent" as possible to the SDHW system group, which can conflict with the desire to have a small sample size. How will adjustment be made for the inevitable differences between the two groups? Is the distribution of draw throughout the group the same? How do the two groups relate to the targeted population in general?

Before-After. Measured electrical usage before the SDHW system is installed is compared against measured usage after the system is installed. The advantage of this technique is that the non-solar reference is the same household, and very little modeling is required. The disadvantages are: 1) data must be acquired over long time frames (likely two years) to eliminate seasonal variation in hot water use, mains temperature, and weather, and 2) systematic bias is present and hard to estimate.

There are a number of bias sources. Occupancy changes generally induce large changes in usage and thus large biases in simple before-after comparisons. Often occupant interviews are used to track occupancy and screen households out of the analysis if occupancy is changed, but this can seriously reduce the sample size. Also, there is the possibility of usage changing by virtue of the presence of the SDHW system. For example, it may be that, since the occupants believe DHW will cost less with an SDHW system, they may use more hot water in the after period. Or, the occupants with a new SDHW system may decide to use less hot water or use it mostly on sunny days to "work with" the new system. There are also seasonal trends in hot water draw (more hot water used in winter) and mains inlet water temperature (inlet temperature decreases in winter). These effects will seriously bias a naive before-after comparison if an entire year of data before and after are not acquired. These effects can be corrected for with an extrapolation based upon SDHW system and conventional system models and DHW usage models based upon measured data. There are probably systematic trends in water usage that are complex in causation and unpredictable. For example, water shortage or excess, and attendant publicity, will drive usage down or up, respectively. This effect can be eliminated to some extent by use of a control group.

On-Off. The SDHW system is switched in and out of the system in a pre-planned sequence, and measured electrical consumption with and without the SDHW system is compared. This design is like a series of repeated before-after tests, and when run for extended periods should eliminate most biases in that design. The period in the "on" state must be large enough to eliminate transient and storage effects, implying at least a week. It will require some means of automatically switching the system in or out, which can be very cumbersome and costly to do. (Occupants could not be relied upon to do this routinely, and, having knowledge of when the system is in place may bias the usage.)

Calculated Reference. The performance of the SDHW system is measured and compared with the reference usage (conventional system) calculated from a model driven by the measured draw of the monitored SDHW system. The advantages include: 1) guaranteed equivalency (within the accuracy of the model) of comparing solar to non-solar alternatives; and 2) reduced monitoring duration. The disadvantages are: 1) the error or uncertainty introduced by modeling; and 2) potential lack of confidence in the reference system model approach by program officials.

5. EXTRAPOLATION

The objective of any monitoring project is to proceed from specific results on the sample systems during the monitoring period to general results for the entire targeted population over the long term. The performance of a given SDHW system is significantly affected by a number of variables including DHW draw statistics, local weather, and mains water temperature. Draw statistics, for example, are a complex function of household characteristics and can vary significantly by time-of-day and from day to day. Extrapolation involves understanding any significant differences between the sample and the target population and adjusting the results as necessary to be representative of the target population. There are similar issues regarding differences between the local weather during the monitoring period versus the expected long-term climate.

Large Samples. One approach is to employ a statistical design, choosing a "large" and "random" sample that is assumed to adequately match the population. Statistical tests of this hypothesis can be done. Because of large per-case variations (perhaps a factor of two on average usage, etc.), even the simplest objective of estimating energy savings (kWh) without data normalization may imply hundreds of system-years must be monitored to attain the desired accuracy. This may not be plausible for a pilot program with a limited number of SDHW systems being tested.

Normalized Results. In an effort to reduce sample size and maximize information obtained, one can make analytical adjustments to the data to accommodate the mismatch between the key determinants of the sample and population. If, for example, one can determine the dependence of kWh reduction on draw statistics, then the results for one distribution can be generalized to other distributions. There are then a number of issues. First, what are the population statistics? Are there any available data on these variables, or must it be determined as part of the project itself? Are studies available relating hot water draw to population demographics, such as number of occupants, income, etc. Can submetered electric load data on conventional systems be used as a surrogate for dynamic draw data? Second, how does one choose a "small" sample that matches the population statistics insofar as possible? Third, how is the monitored data actually adjusted to account for the mismatches between sample and population?

Calibrated Models. A model of the SDHW system, calibrated based on measured data from each SDHW system type, is used under target population draw, mains temperature and weather conditions to predict long-term performance of the SDHW system. The advantages are: 1) the system need be monitored only for sufficient time to calibrate the model, drastically reducing testing time and costs, and 2) the analysis can include a wide variety of "what if" variations, such as asking what would performance have been if load control devices had also been installed or operated differently. Similar questions regarding population statistics apply here as discussed in the previous paragraph. A disadvantage is the potential lack of confidence in modeling by program officials who are unfamiliar and uncomfortable with this approach (this may dictate some sort of longer-term validation study).

Test-Based Models. The operating conditions of the installed solar water heating system can be manipulated in an attempt to obtain more robust estimates of system parameters and/or obtain them in a shorter time period than in the calibrated model approach which depends on the naturally occurring changes in the operating conditions to elicit the system parameters. The test-based model approach shares the advantages and disadvantages listed above for the calibrated model approach. The advantage is that the parameter estimates may be more robust and/or obtained in a shorter time period. The disadvantage is that more intervention during testing is required.

6. RECOMMENDED APPROACHES

Pros and cons for different monitoring approaches are discussed in this section and summarized in Table 1. Recommended approaches are shown in Table 2 based on limitations in accuracy and data types. For exsample, billing analysis does not involve the type of data needed for demand impact evaluation nor does it have adequate accuracy for individual sites to support analysis of as-built performance, persistence of savings, or model validation. Also implicit in Table 2 are assumptions about finite project budgets, e.g., detailed monitoring is not recommended for studying as-built performance or persistence of saving, because these objectives require medium/large sample sizes, and detailed monitoring would be prohibitively expensive.

Energy Impacts. Energy impact evaluation requires extrapolation from the monitored sample to a more general population and estimation of the reference water heating energy use. This is best accomplished by billing analysis and/or detailed monitoring. Billing analysis allows very large samples up to the entire population of interest and before/after estimation of the reference water heating energy use. Detailed monitoring can be used with the calibrated model approach to extrapolation and calculated reference water heating energy use.

Demand Impacts. Demand impact evaluation is a very challenging objective for monitoring projects. Because peak demands occur infrequently and under very specific combinations of weather and hot water use patterns, it is difficult to extrapolate from the monitored sample to a larger population consisting of households. Direct monitoring for demand impact evaluation would require the combination of relatively detailed monitoring and large sample sizes. Alternatively, the recommended

TABLE 3. Pros and Cons of Monitoring Approaches

Objective	Level	Pros:	Cons:
Energy Impacts	Billing Analysis	- No instrumentation required - Very large samples possible	- Imprecise for individual households - Large samples required - Control group or before/after required - Not applicable if solar accompanied by other conservation measures
	End-Use Metering	- Low-cost - Large samples possible	- Control group or before/after required
	Btu Metering	- Includes temperature measurements	- More expensive than end-use metering
	Detailed Monitoring	- Calibrated model for extrapolation	- High-cost
Demand Impacts	Billing Analysis	- Not applicable	- Not applicable without demand meter
	End-Use Metering	- Low cost	- Requires demand meter - Does not record conditions causing peaks
	Btu Metering	- Relatively low cost	- Requires demand meter - Does not record conditions causing peaks
	Detailed Monitoring	- Calibrated model for extrapolation	- High-cost
Persistence	Billing Analysis	- Not applicable	- Not applicable due to probable changes in other building energy uses over time
	End-Use Metering	- Low-cost - Large samples possible - Extended monitoring periods possible	- Uncertainty regarding temperatures
	Btu Metering	- Direct measurement of solar performance	- More expensive than metering
	Detailed Monitoring	- Not applicable	- Not applicable due to high cost
Validation	Billing Analysis	- Not applicable	- Not applicable due to lack of detail
	End-Use Metering	- Low cost	- No detail for diagnostics
	Btu Metering	- Low cost	- Little detail for diagnostics
	Detailed Monitoring	- Detailed information	- High cost

approach is detailed monitoring using the calibrated model for extrapolation and the calculated reference method.

Of course, if the issue is contribution to summer peak demand, and energy monitoring indicates that a solar water heating system is providing 100% of the energy required for water heating during summer months, then demand impact monitoring of the solar water heating system is unnecessary since the electric demand is zero.

As-Built Performance. If the objective is to be able to detect non-performing and partially performing systems, and such systems are expected to be a small percentage of the total installed systems, then a relatively large percentage of installed systems needs to be monitored in order to accurately detect the percentage of failed systems. A reasonable level of accuracy in estimating the performance of each SDHW system is also required in order to assess performance compared to predicted performance. End-use metering is the recommended approach representing the best combination of low cost and reasonable accuracy.

TABLE 4. Recommended Field Monitoring Approaches

	Billing Analysis	End-Use Metering	Btu Metering	Detailed Monitoring
Energy Impact	X			X
Demand Impact				X
As-Built		X	X	
Persistence		X	X	
Validation			X	X
Data Detail	→	→	→	→
Sample Size	←	←	←	←

Persistence of Savings. Assessing persistence of savings has requirements that are similar to those for as-built performance assessment with the added requirement that the instrumentation be left in the field for extended time periods. End-use metering is the recommended approach.

Model Validation. For model validation, detailed monitoring is needed. Only a few sites are needed per system type, because the driving forces (weather conditions and hot water use patterns) will be carefully monitored, and only need to be within the typical range of normal SDHW system operation, not in any way a statistically representative sample of the more general population.

7. CONCLUSIONS

The design of a monitoring program for SDHW systems depends upon the specific objectives of the project and cannot be logically chosen until the objectives are clearly stated. The major categories of experiment design have been stated, and the most useful experiment designs outlined. Design for a specific project is clearly a complex process. Knowledge of the product performance, of the errors in monitoring, and statistics is required.

Large sample (purely statistical) approaches may be impractical for monitoring SDHW system performance, especially for determination of demand reduction. Under these circumstances, there may be significant advantages to: 1) the calibrated (or test-based) model approach for extrapolation from the sample results to long-term target results for the target population, and 2) the calculated reference approach for determination of the non-solar system performance.

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